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Economic impacts of installing solar power plants in northern Chile

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ABSTRACT

Chile has one of the best worldwide conditions for the generation of electrical energy from solar resources, having an annual average Direct Normal Irradiation (DNI) of 9–10 kWh/m^2/day. Many important astronomical observatories have been installed in the north of Chile because of the low number of cloudy days and the high sky clearness index. Also, in the north of Chile, there are many mining companies who demand large amounts of load for their operation. They currently use electricity provided from fossil fuels thermoelectric plants (99% of the electrical generation of the Northern Interconnected Power System is thermoelectric) that are subject to fuel-price volatilities and have large global and local impacts on the environment.

The work reported in this paper focuses on identifying a limited number of variables, which explain the variations on the investment cost of solar power plants, and use this information to assess the economic benefits of the installation of this type of plants in the north of Chile. In particular, multiple linear regressions were formulated, with information about 45 thermal and 37 photovoltaic existing and projected solar plants, to explain the variations among the investment cost of the different projects. We determine a limited number of variables that adequately explain the variations of the investment cost of solar energy power plants. Using these results, 11 technologies were simulated in four locations to assess the economic impact of these projects in terms of the change induced in the marginal cost of the system and the net present value of the 44 projects. We show that installing a solar power plant in the north of Chile will not bring net economic benefits for the power sector unless current conditions on factors such as carbon bond prices, labor rate, or solar-plant part prices change. The break even capital cost and energy cost for a Stirling Dish solar plant in Calama are 2.33 millions of USD/MW and 9.3 cents/kWh, respectively.

Contents

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1. Introduction

Chile has one of the best worldwide conditions for the generation of electrical energy from solar resources, having an annual average Direct Normal Irradiation (DNI) of 9–10 kWh/m^2/day [1]. Many important astronomical observatories have been installed in the north of Chile because of the low number of cloudy days and the high sky clearness index, which is traduced into high amount of solar radiation received and more potential of generation of electric energy than other locations.

Moreover, in the north of Chile, there are many mining companies who demand large amounts of load for their operation. They currently use electricity provided from fossil fuels thermoelectric plants (99% of the electrical generation of the Northern Interconnected Power System is thermoelectric) that are subject to fuel-price volatilities and have large global and local impacts on the environment. On the other hand, environmental regulations are getting stricter and customers are demanding companies to make a reduction on greenhouse gas (GHG) emissions and mitigating their carbon footprints.

There is strong evidence that solar technologies can have a major impact on the future energy mix of countries with a high solar resource [2]. However, the current literature has limited applicability for Chilean energy generation companies because of the unconsciousness of the variables that explain the cost structure associated to a solar power plant installed in Chile. Nonetheless, it is interesting to analyze the economic impact for the electricity supply sector of installing solar power plants in Northern Chile, in terms of the net present value of the solar projects and the change induced in the marginal cost of the system.

For different applications, researchers have used multivariate regression models to characterize cost functions. For instances, in [3], the authors determine the construction cost of a nuclear power plant using multivariate regression models, while, in [4], the authors use multivariate regression models for determining the US roadwork construction contract price. Regression models are also used to calculate the hospital costs in different countries, as a function of their size and type (private or public), in [5], and to estimate airports' cost functions in [6].

Investment costs have also been estimated using other models. In [7], the authors use a bottom-up approach, based on current technologies and expected market conditions for 2012–2017, to estimate the installation cost of an off-shore wind power plant in the US.

In Chile, some authors [8–10] have studied different aspects related with the measurement of the solar energy availability. There are also some studies [11,12] about the technical feasibility of installing solar thermal power plants in the north of the country and a study [13] estimating the levelized energy costs for CSP power plants in northern Chile. These studies focus mainly on the resource measurement and the technical challenges. Differently, the present work focuses on the economic impacts of installing solar thermal and solar photovoltaic power plants.

In other countries, several cost studies have been performed. In [14], the solar photovoltaic levelized electricity cost is estimated. The risk associated to solar power investments are studied in [15], in the context of North Africa. In the same context of North Africa, the cost of reducing water use of concentrating solar power is analyzed in [16]. An economic analysis of power generation from parabolic trough solar thermal plants in Cyprus is performed in [17]. The technology development, cost development and life cycle inventories for concentrated solar power in Africa and Europe are assessed in [18]. In [19], the authors study the influence on electricity cost of solar capacity factors and energy storage. The interaction between market economics and policy, in the context of high penetration of solar energy, is studied in [20].

Social benefits of solar power plants have been studied in [21,22], where the authors perform cost-benefit analyses of installing a PV plant in the Turkish power system. They found that this installation is not economically feasible because of its high investment cost.

This paper has two main contributions. A first contribution is to identify the variables (such as technology, installed capacity, area, generation, construction year, among others) that explain the variations on the investment costs of solar energy power plants. The second contribution of the paper is the assessment of the economic impact that will cause the installation of a solar power plant in the Northern Interconnected Power System of Chile (SING).

The rest of the paper is organized as follows. Section 2 gives a brief overview of solar power generation technologies. Section 3 provides the econometric analysis made to characterize the cost structure associated to a solar power plant installed in Chile. Section 4 presents the simulations of the Northern Interconnected Power System of Chile performed considering the installation of new solar power plants. Section 5 concludes the paper.

2. Solar energy

Solar energy is obtained from radiant light and heat from the Sun. In the north of Chile, solar radiation is very high compared to other places of the world. However, the solar radiation levels still vary across seasons. Fig. 1 shows the monthly average global horizontal irradiation (GHI) for Calama in northern Chile, where the impacts of installing solar power plants are studied in this work.

Solar technologies transform the solar radiation in electric energy and can be grouped in two families: Thermal and Photovoltaic. Solar thermal technologies use irradiation as a source of heat to raise the temperature of a fluid. To minimize the land usage and maximize the efficiency, the sunlight is concentrated onto receivers. Electric energy can be generated via a steam turbine or a heat engine connected to a generator. Solar Photovoltaic technologies convert solar radiation into direct current due to the photovoltaic effect.

In this article, three solar thermal technologies are considered: parabolic trough, solar power tower (both of which can include energy storage with molten salt tanks) and Stirling dish technology. As well, three solar photovoltaic technologies are considered: monocrystalline silicon and polycrystalline silicon (both of which could include different tracking options) and First Solar Cadmium Telluride (CdTe) Thin-film.

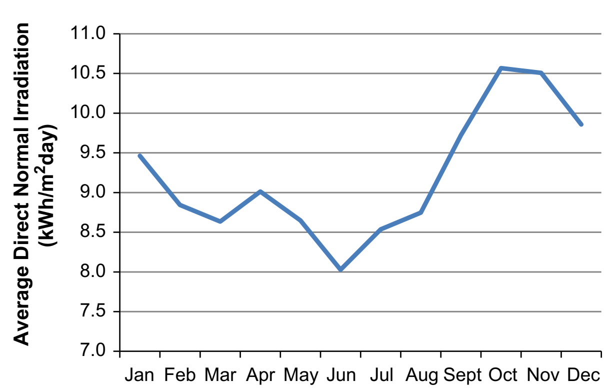

Fig. 1. Average Global Horizontal Irradiation (DNI) for Calama, Chile. Source: [1].

As mentioned earlier, solar power plants of these technologies are studied to determine an adequate investment cost function to later determine the economic impact of solar plants located in Chile and simulate these plants in the Northern Interconnected Power System of Chile.

3. Econometric analysis

Data from 45 thermal solar plants and 37 photovoltaic solar parks were used for determining an adequate investment cost function for the different technologies of solar power generation. Several variables were chosen and studied to determine their significance on the investment cost of the power plants. Since the variables that mostly explain the investment cost of thermal and photovoltaic power plants are different, the econometric analysis was separated in two regression models: thermal and photovoltaic.

From the total of 45 thermal solar plants, 15 are currently in operation, 14 are under construction, and 16 are proposed projects. All the photovoltaic solar parks studied are currently in operation with the only exception of Calama Solar One, which is a proposed project in Chile.

3.1. Solar thermal regression model

The studied variables (the ones for which data were collected) of the thermal solar plants are total installed cost, technology, power capacity, storage capacity, installed country, year of commissioning, mirror solar field, electricity generation, capacity factor, total plant area, and radiation.

Using different combinations of these variables, several multivariable linear regressions were performed to determine the main explanatory variables (i.e., the ones with the highest statistical significance levels) and the coefficients that determine the total investment or installed cost of a solar power plant with the best fit. We found that the main explanatory variables for the investment cost of thermal solar power plants are capacity, technology, total area, storage capacity and installed country. Using these variables, we formulate a multivariable linear regression with an R-Squared of 98.2%, which is shown in (1).

$$\text{Investment cost} = \beta_0 + \beta_1\ \text{Capacity} + \beta_2\ \text{Area} + \beta_3\ \text{Storage\_Capacity} + D_{\text{Technology}} + D_{\text{Country}} \quad (1)$$

where β_0=−54.7503, β_1=2.9487, β_2=0.277, β_3=0.2661, and $D_{\text{Technology}}$ and D_{Country} are given as follows:

$$D_{\text{Technology}} \begin{cases} 0 & \text{if Parabolic trough} \\ -430.7149 & \text{if Stirling dish} \\ -198.2550 & \text{if Solar tower} \end{cases}$$

$$D_{\text{Country}} \begin{cases} 0 & \text{if Chile} \\ 168.098 & \text{if Spain} \\ 57.89 & \text{if USA} \end{cases}$$

Eq. (1) shows the investment cost function for thermal solar power plants, in millions of US dollars, as a function of the capacity (in MW), the area utilized (in hectares), the storage capacity (in hours of storage per capacity in MWh), the technology employed (parabolic trough, Stirling dish and solar tower), and the country of installation (Chile, Spain, USA).

In statistics and econometrics, particularly in regression analysis, a dummy variable (also known as an indicator variable) is one that takes the values 0 or 1 to indicate the absence or presence of some categorical effects that may be expected to shift the outcome. In (1), we use dummy variables to consider the absence or presence of the influence of the technology and the country in the investment cost.

Table 1
Parameter estimates for thermal investment cost regression model.

Variables	Coefficient	Std. Err	*t*	$P>\lvert t\rvert$	Beta
Capacity	2.948655	0.6396	4.61	0	0.76345
Storage Capacity	0.26609	0.06525	4.08	0	0.13446
Area	0.277026	0.1853	1.49	0.143	0.28517
Dummy Stirling	−430.715	158.17	−2.72	0.01	−0.0959
Dummy Tower	−198.256	45.96	−4.31	0	−0.1085
Dummy Spain	168.0975	124.97	1.35	0.187	0.1266
Dummy USA	57.89	127.704	0.45	0.653	0.0432
Constant	−54.75	120.046	−0.46	0.651	–

Table 1 shows the estimated parameters of the multiple-regression model. The first column corresponds to the chosen independent variables for predicting the installed cost of the solar plant. The following columns show the coefficient of the regression equation (for those variables); the standard errors associated with the coefficients; the *t*-statistics used in testing whether a given coefficient is significantly different from zero or not; the two-tailed *p*-values ($P>\lvert t\rvert$) used in testing the null hypothesis that the coefficient is 0, using an alpha of 0.05; and the standardized coefficients (Beta) that measure the change of the dependent variables (in standard deviation) produced by a unitary change in the independent variable (in standard deviation), maintaining the rest of the variables constant. These Beta coefficients allow us to identify which independent variables have the biggest impact (or significance) in explaining the model.

From Table 1, we observe that capacity, storage capacity, and area are variables with a positive sign of the coefficients, implying that the investment cost would increase with an increment on these variables.

The last column in Table 1 indicates that the capacity of the plant is the variable having the highest impact on explaining the model; then we have total area, the storage capacity, the installed country, and finally the technology used.

It is interesting to remark that our results indicate that Chile is the less expensive country for the installation of a solar power plant. On the other hand, Stirling-dish systems have the lowest investment cost of all technologies, followed by solar tower and then parabolic trough. It is important to consider that the regression had 37 parabolic-trough plants, seven solar-tower plants and only one Stirling-dish plant.

It may be surprising that radiation was not included as a significant explanatory variable in the model. This is mainly because the installation country explains it with a correlation of 96%. In addition, the installation country explains labor-work cost and other variables.

3.2. Solar photovoltaic regression model

The studied variables of the photovoltaic solar parks are total installed cost, technology, power capacity, installed country, year of commissioning, total plant area, electricity generation, capacity factor, and radiation.

As in the case of the thermal regression model, several multivariable linear regressions were formulated with different combinations of the variables. It was found that the main explanatory variables (i.e., the ones with the highest statistical significance levels) for the investment cost of photovoltaic solar power plants are capacity, technology, year of commissioning and installed country. Using these variables, we formulate a multivariable linear

regression with an R-Squared of 96.4%, which is shown in (2).

$$\text{Investment cost} = \beta_0 + \beta_1 \text{ Capacity} + \beta_2 \text{ Year} + D_{\text{Technology}} + D_{\text{Country}} \quad (2)$$

where β_0=29,594, β_1=8.59, β_2=-14.74, and $D_{\text{Technology}}$ and D_{Country} are given as follows:

$$D_{\text{Technology}} \begin{cases} 0 & \text{if 1-Axis monocrystalline silicon} \\ -30.9 & \text{if 1-Axis polycrystalline silicon} \\ -21.1 & \text{if 2-Axis polycrystalline silicon} \\ -173.4 & \text{if First solar cadmium telluride} \\ 26.8 & \text{if Monocrystalline silicon} \\ -38.3 & \text{if Polycrystalline silicon} \end{cases}$$

$$D_{\text{Country}} \begin{cases} 0 & \text{if Germany} \\ -16.2 & \text{if Italy} \\ 17.8 & \text{if Korea} \\ -21.8 & \text{if Spain} \\ 5.85 & \text{if USA} \\ -34.7 & \text{if Chile} \end{cases}$$

Eq. (2) shows the investment cost function for photovoltaic solar power plants, in millions of US dollars, as a function of the capacity (in MW), the year of installation, the technology (polycrystalline and mono-crystalline silicon with different tracking, and first solar cadmium telluride thin film) and the installation country (Germany, Italy, Korea, Spain, USA, and Chile). In (2), we use dummy variables to consider the absence or presence of the influence of the technology and the country in the investment cost.

Table 2
Parameter estimates for photovoltaic investment cost regression model.

Variables	Coefficient	Std. Err	t	$P>\|t\|$	Beta
Capacity	8.591	0.3966	21.66	0	1.09
Year	−14.742	11.122	−1.33	0.198	−0.077
Dummy Poli-Si	−38.3	19.234	−1.99	0.058	−0.167
Dummy Poli-Si-1a	−30.964	23.637	−1.31	0.203	−0.085
Dummy Poli-Si-2a	21.094	20.836	1.01	0.322	0.069
Dummy Mono-Si	26.828	23.794	1.13	0.271	0.054
Dummy FS-CdTe	−173.355	33.727	−5.14	0	−0.348
Dummy Italy	−16.18	42.004	−0.39	0.704	−0.0446
Dummy Korea	17.849	40.522	0.44	0.664	0.0257
Dummy Portugal	−21.818	36.111	−0.6	0.552	−0.0529
Dummy Spain	−5.855	52.513	−0.11	0.912	−0.0084
Dummy USA	39.515	40.025	0.99	0.334	0.1643
Dummy Chile	−34.69	40.283	−0.86	0.398	−0.069
Constant	29,594.06	22,354	1.32	0.199	–

Table 2 shows the estimated parameters of the multiple-regression model. Note that the installation year has a negative-sign coefficient, which is consistent with the current literature about investment costs [13]. As well, in Table 2, we observe that First Solar Cadmium Telluride Thin Film is the technology that has the lowest investment cost (with a statistically significant coefficient of −173).

The last column in Table 2 indicates that the capacity of the plant is the variable having the highest impact on explaining the model; then we have the technology and the country (if we look at the factor for First Solar Cadmium Telluride Thin Film and USA, respectively), and finally we have the installation year.

The obtained cost information for the different technologies of solar power is used in the next section to simulate the long-term operation of the Chilean Northern Interconnected Power System.

4. Chilean northern interconnected power system simulation

Due to the narrow and long features of the Chilean territory, Chile has four independent power networks. These are: (i) the Northern Interconnected System (SING), providing energy to the north zone, where the main mining industry is located, (ii) the Central Interconnected System (SIC), providing energy to the central and south regions, where most of the population lives, (iii) the Aysén System, a small isolated system in the extreme south of Chile, and (iv) the Magallanes System, which covers another isolated area in the extreme south of Chile.

The Chilean SING system is a 220 kV and 500 kV AC power system with none back to back HVDC lines. The installed generation capacity in the Chilean SING power system in 2011 was 4585 MW, with an annual consumption of 15,889 GWh [23].

We simulate the long-term operation of the Chilean Northern Interconnected Power System (SING) to assess the economic impact of installing a solar power plant in the SING.

We utilize the *OSE2000©* software [24], which uses Stochastic Dual Dynamic Programming (SDDP) to optimize the operational and total system cost, estimating the optimal future energy prices for each node of the system. We consider a horizon of 11 years (consistently with the information available about the operation of the SING and about the new power plants to be incorporated in the future to the system).It is important to mention that *OSE2000©* uses hourly information to perform the

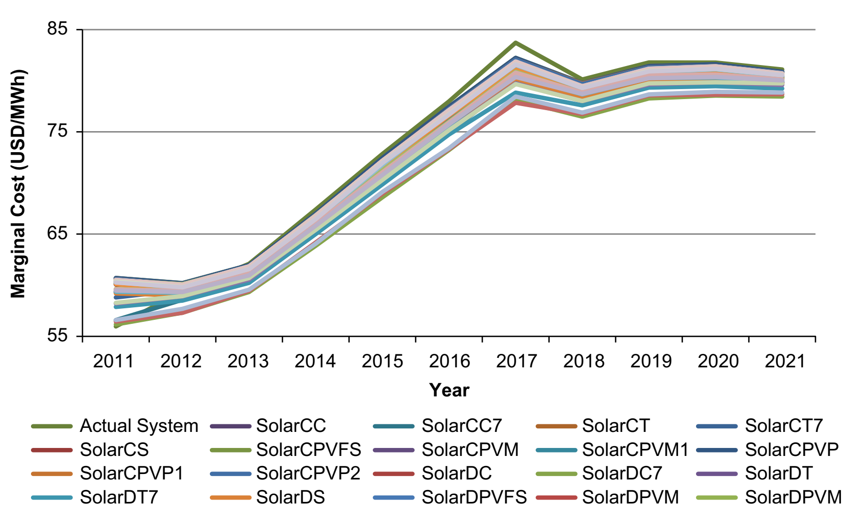

Fig. 2. Marginal system cost for actual system and for new solar scenarios.

long-term operation of the SING; which is an important feature in the case of solar power plants due to the significant differences in solar generation through the day. Moreover, the *OSE2000*© software assumes that the electricity market is perfectly competitive and the demand is perfectly inelastic. This software is widely used by Chilean regulators and electrical companies to estimate future prices and plan the grid expansions.

We simulate 44 different scenarios, considering 11 different technologies and four installation sites within the SING. Each of the 44 scenarios corresponds to only one solar power plant added to the system. Then, each scenario was compared with the actual operation of the system.

The installation sites chosen for the simulations are Calama, Dolores, Pozo Almonte, and Tamarugal, since these are the sites with the highest energy prices and the highest solar radiations within the SING.

There are different ways for estimating solar-radiation and weather information [25–27]. In this work, Meteonorm© 6.0 software [28] information was used, which has satellite information from the National Renewable Energy Laboratory (NREL) and NASA together with statistical and mathematical models to predict hourly information.

The generation capacities of the simulated power plants are 200 MW for thermal technologies and 100 MW for photovoltaic technologies. The reasons for choosing those values are that (i) the investment cost is the lowest for thermal power plants with capacities over 200 MW [29], and (ii) photovoltaic technologies are modular, where 100 MW was calibrated in *OSE2000*© for creating a no-negligible impact in the total system cost.

The amount of energy generated from the different solar technologies was obtained by using the Solar Advisor Model (SAM©) software, version 2010.4.12 [30].In particular, hourly energy generation for a complete year was simulated, using SAM©, for parabolic trough, solar tower, Stirling dish, First Solar CdTe, polycrystalline and mono-crystalline silicon for a fixed position and for one-axis and two-axis tracking.

This hourly generation information was included in the *OSE2000*© model, along with the information about the energy self-consumed by the new solar power plants and about the current operation of the SING (demand, marginal costs of productions, available generation capacities, available transmission capacities, etc.). The outcome of the simulation includes the total system cost, the operational system cost, and the total generation-company income for the installed solar plant, among other information.

4.1. SING simulation outcome

The total system cost and the marginal cost of the system for the horizon of 11 years are obtained directly from the *OSE2000*© simulation. Fig. 2 shows the evolution over time of the marginal cost of the system, when incorporating the different types of solar power plants. The same general pattern is followed by every curve in Fig. 2 because the addition of any single of these solar power plants has a small effect on the overall energy production cost of the system. Major effects are related to the grid infrastructure plan, which is considered the same in all cases.

A solar power plant using parabolic trough technology with 7 h of storage is the one with the highest reduction in the marginal cost of the system. From Fig. 2, we note that the location of the power plant (among the four selected sites) does not have a significant impact on the system marginal cost. If we would install a 200 MW solar parabolic trough power plant with 7 h of storage in Dolores, there would be an average decrease of 3.3 USD/MWh in the marginal cost of the system with respect to the actual system operation. In this case, the largest difference from the system marginal cost of the actual (i.e., business-as-usual) situation would happen in year 2017, reaching 5.6 USD/MWh.

Table 3
Nomenclature format for technology.

Symbol	Technology
C	Parabolic trough
C7	Parabolic trough with 7 h of storage
T	Solar power tower
T7	Solar power tower with 7 h of storage
S	Stirling dish
PVFS	First solar CdTe thin film PV
PVM	Mono-crystalline silicon PV
PVM1	Mono-crystalline silicon PV with one axis tracking
PVP	Polycrystalline silicon PV
PVP1	Polycrystalline silicon PV with one axis tracking
PVP2	Polycrystalline silicon PV with two axis tracking

The nomenclature used in the references of the figures follows the following format: Solar[place][technology], where the notation for the place is: C=Calama, D=Dolores, T=Tamarugal, and PA=Pozo Almonte and the notation for the technology is given in Table 3.

4.2. Elements for the economic evaluation

For the economic evaluation on the lifetime of the new solar power plant, a horizon of 30 years was chosen. The *OSE2000*©'s 11 year output was projected until 2040 using a linear fit curve for all the cases, following the historical trend.

Next we detail the calculations associated to every component of the economic evaluation.

4.2.1. Carbon credits

For all the solar projects considered here, carbon credits were included as benefits throughout the years of operation. Because there are no solar power plants currently installed in Chile, an emission factor of 0.57 $TonCO_2$/MWh (that was approved by the United Nations Framework Convention on Climate Change (UNFCC) for Canela Wind Farm project in Chile) [31] was used in this study. The benefits from carbon credits are added to the economic evaluations of every solar plant using a price of 18.42 USD/$TonCO_2$, which approximately corresponds to the average price of carbon bonds traded during the first half of 2010 in the European Market Exchange [32].(We use the equivalence 1 Euro=1.2292 USD).

Fig. 3 shows the annual benefits in millions of USD that the different solar technologies would obtain from carbon credits for a solar power plant installed in Calama. Differences are because each technology has a different capacity factor so they generate a different amount of electric energy throughout the year.

4.2.2. Income from energy generation

Annual private income from energy generation, in million of USD, is shown in Fig. 4 for the different solar technologies located in Calama. These values were obtained from the linear projection of the *OSE2000*© simulation outcome.

4.2.3. Income from power capacity payments

In Chile, generation companies receive a capacity payment for their installed power capacity, if it is considered that they contribute to the energy reserves in case of a contingency. The last report from Chilean Energy Commission (CNE) stated a price

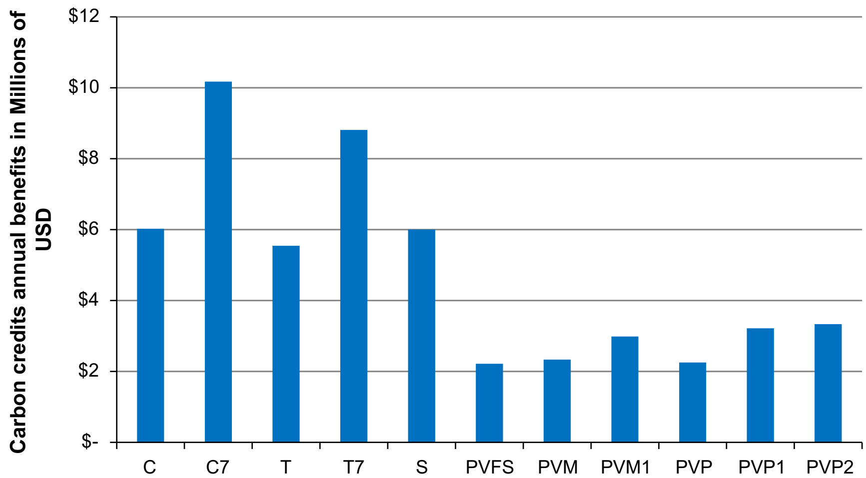

Fig. 3. Annual income from carbon credits for solar plants in Calama, Chile.

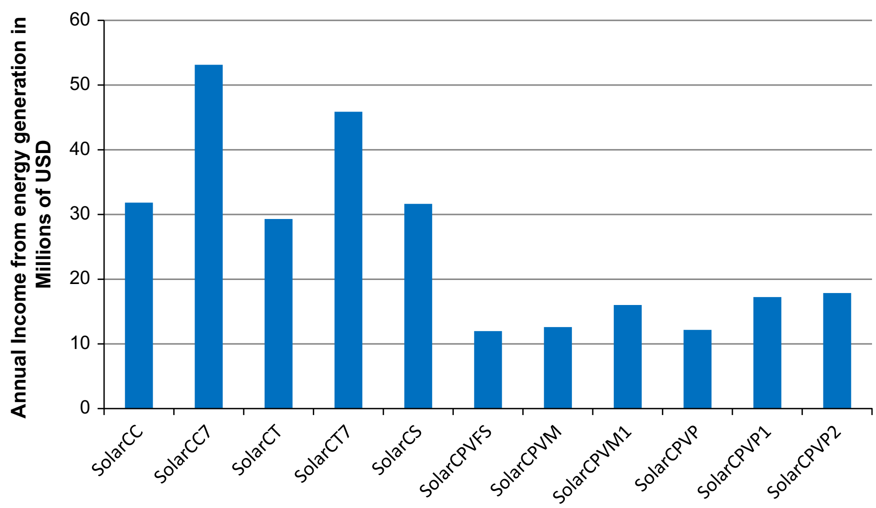

Fig. 4. Annual income from energy generation for solar plants in Calama, Chile.

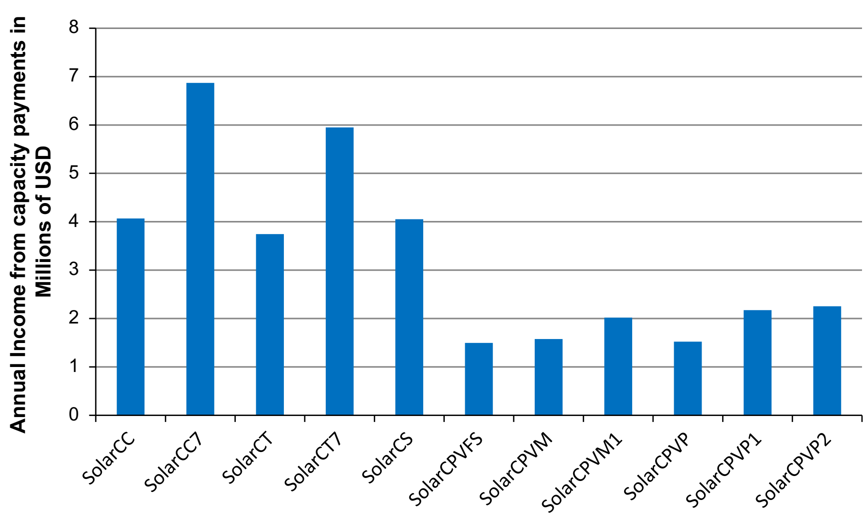

Fig. 5. Annual income from installed power for solar plants in Calama, Chile.

of 8.7142 USD/kW/months equivalent to 0.105 USD/MW/year for firm power [33]. Eq. (3) shows how the annual income from power capacity payments is calculated. To obtain this income, we use the firm power preliminary factor (FPPF), which establishes the percentage of firm power that a certain power plant can provide [34]. We use a FPPF of 0.606, which was used for wind

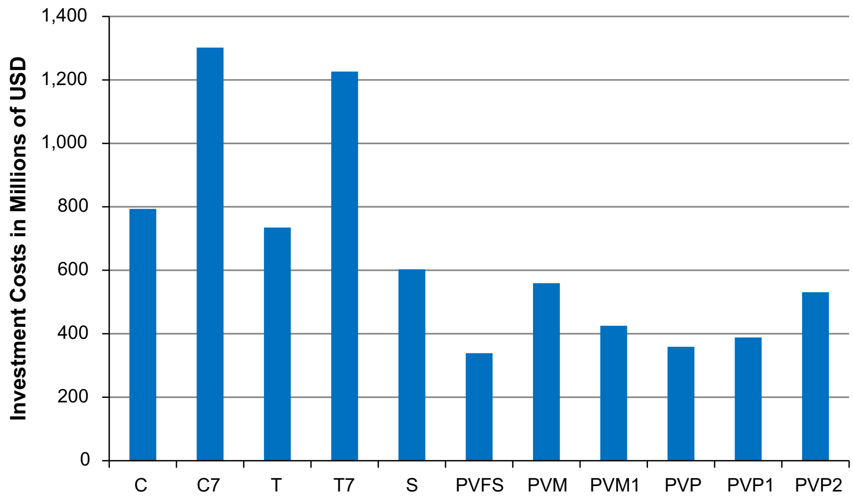

Fig. 6. Investment cost for solar plants in Chile.

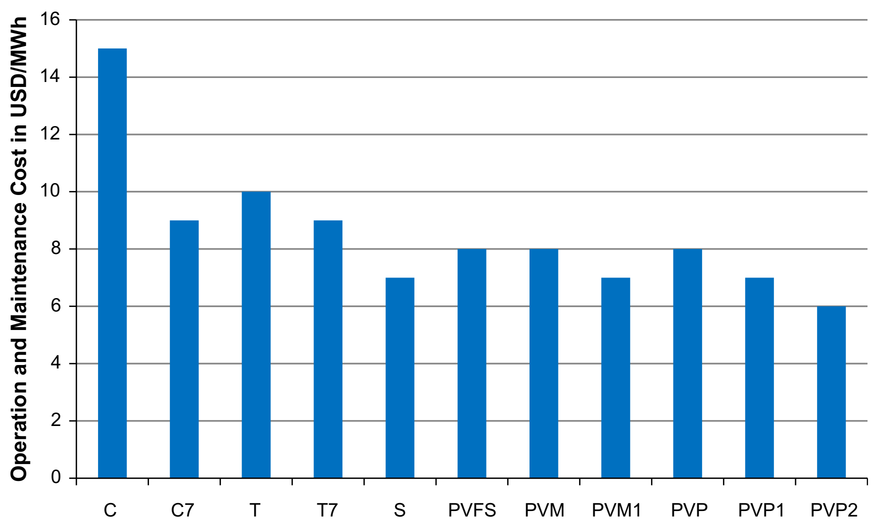

Fig. 7. Operation and maintenance cost for a solar plant in Chile.

farms in Chile [31].

$$\text{Income} = \text{Capacity} * \text{Capacity Factor} * \text{Firm Power Price} * \text{FPPF} \tag{3}$$

Fig. 5 shows the annual income from power capacity payments, in millions of USD, for the different solar technologies located in Calama.

4.2.4. Investment costs

We use the multivariable linear regression results of Section 3 to obtain the investment costs of the considered solar power plants installed in Chile.

Recall that we look for the investment costs of thermal power plants with a capacity of 200 MW and photovoltaic (PV) power plants with a capacity of 100 MW. While the data used for obtaining the multivariate linear regression model for thermal power plants consisted of a wide range of capacities, this is not the case for PV power plants. The data used for obtaining the multivariate linear regression model for PV power plants consisted of different capacities in the range of 6–60 MW depending on the technology. Thus, PV plants with 100 MW are not in the range of the data used in the multivariate linear regression model. For addressing this issue, and because PV technology is modular, we assume the use of modules of PV technology with a capacity equal to the average of the capacities of the PV power plants used as data in the regression model.[1] That is, we use two blocks of 50 MW for First Solar thin-film (PVFS), five blocks of 20 MW for mono-crystalline silicon (PVM) and polycrystalline with two-axis tracking (PVP2) and four blocks of 25 MW for the rest (PVM1, PVP, PVP1).

Fig. 6 shows the investment costs, in millions of dollars, of the different solar generation technologies. The figure shows that the cost of mono-crystalline photovoltaic (PVM) technology is higher than the same technology with one-axis tracking (PVM1). This unexpected result is explained because most of the power plants that use one-axis tracking belong to Sun Power Corp., which is one of the market leaders of this technology, having the lowest costs. We assume Chile is not manufacturing any PV panel or PTC collector, as it is in the actual case. Currently, Chile imports them mainly from the US, Europe and China. In addition, we do not

[1] For example, polycrystalline technology has 15 different plants, with a capacity range of 6–60 MW. It was chosen a block of 20 MW because the average capacity of the 15 plants is approximately 20 MW.

consider capital expenditures for renovation and modernization as a cost component (which may be obtained from [35]).

4.2.5. Operational and maintenance costs

Operational and maintenance cost for thermal technologies were taken from projects of the California Energy Commission [36] (since a multiple linear regression was not successful on providing this information), using an average cost per each technology. For PV technologies, information from the US Department of Energy's 2008 solar technologies market report was used [37]. Fig. 7 shows the operational and maintenance cost, in USD/MWh, of the different solar generation technologies.

4.3. Economic evaluation results

We performed two different economic evaluations: one denoted as "social", which corresponds to the economic evaluation considering the entire power sector as a whole, and other denoted as "private", which corresponds to the economic evaluation considering only the impacts on the new solar power plant (without taking into account the negative externality produced to the other generation companies).

For the social net present value (NPV), the benefits are measured as the difference between the actual system total cost and the total cost of the system including the new solar power plant. For the private net present value (NPV), the benefits are measured as the sum of the monetary income of the solar power plant from energy sales, capacity payments, and carbon credit sales. We use an interest rate of 6% for computing the social NPV and of 8% for computing the private NPV.

Tables 4 and 5 show the social economic evaluation (in millions of US dollars) for a power plant located in Calama.

It is important to mention that this social economic evaluation does not include the social benefits of the solar power plants in terms of the improvements in the power-system reliability. On the other hand, contrary to what happens in the private economic evaluation, the social economic evaluation does capture the economic disadvantage over the other-technology plants of the system produced by installing a solar power plant (due to the lower marginal cost produced when installing a solar power plant).

The results of the social economic evaluations of every solar power plant analyzed are shown in Fig. 8. This figure shows that, under the current market conditions, installing a solar power

Table 4
Social NPV (rate = 6%) for a thermal plant located in Calama, Chile [a] (amounts in millions of US dollars).

Technology	C	C7	T	T7	S
Social NPV	−367.98	−513.36	−314.73	−545.15	−74.91

[a] The technology notation is as explained in Table 3.

Table 5
Social NPV (rate = 6%) for a PV plant located in Calama, Chile (amounts in millions of US dollars).

Technology	PVFS	PVM	PVM1	PVP	PVP1	PVP2
Social NPV	−159.44	−369.37	−172.73	−176.11	−114.45	−242.3

Table 6
Private NPV (rate = 8%) for a thermal plant located in Calama, Chile (amounts in millions of US dollars).

Technology	C	C7	T	T7	S
Private NPV	−308.92	−438.24	−263.74	−469.31	−97.68

Table 7
Private NPV (rate = 8%) for a PV plant located in Calama, Chile (amounts in millions of US dollars).

Technology	PVFS	PVM	PVM1	PVP	PVP1	PVP2
Private NPV	−140.21	−330.69	−158.5	−155.54	−108.19	−225.13

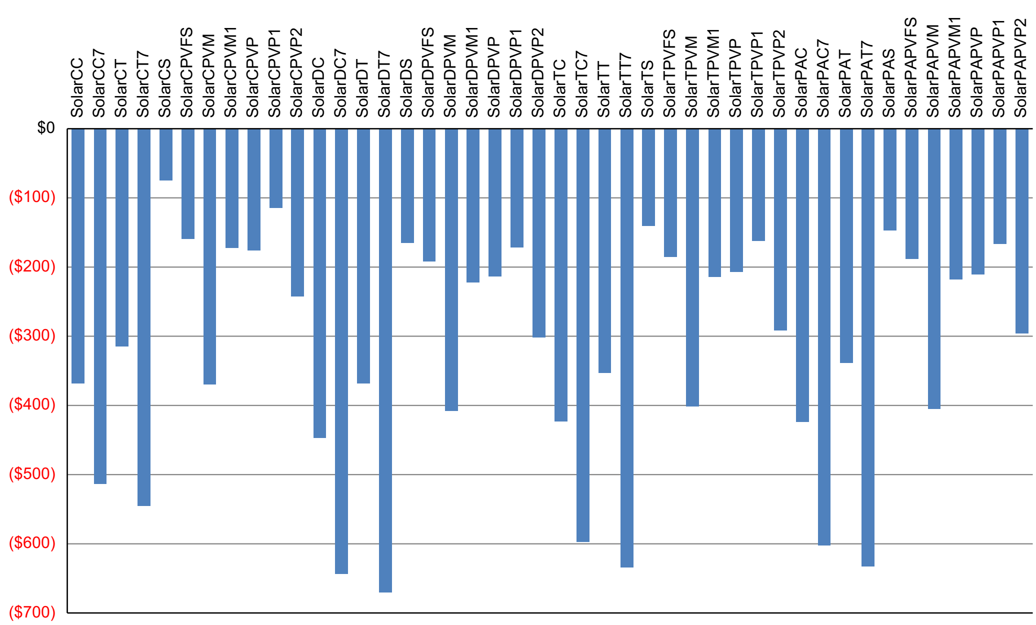

Fig. 8. Social NPV of the different solar power plants.

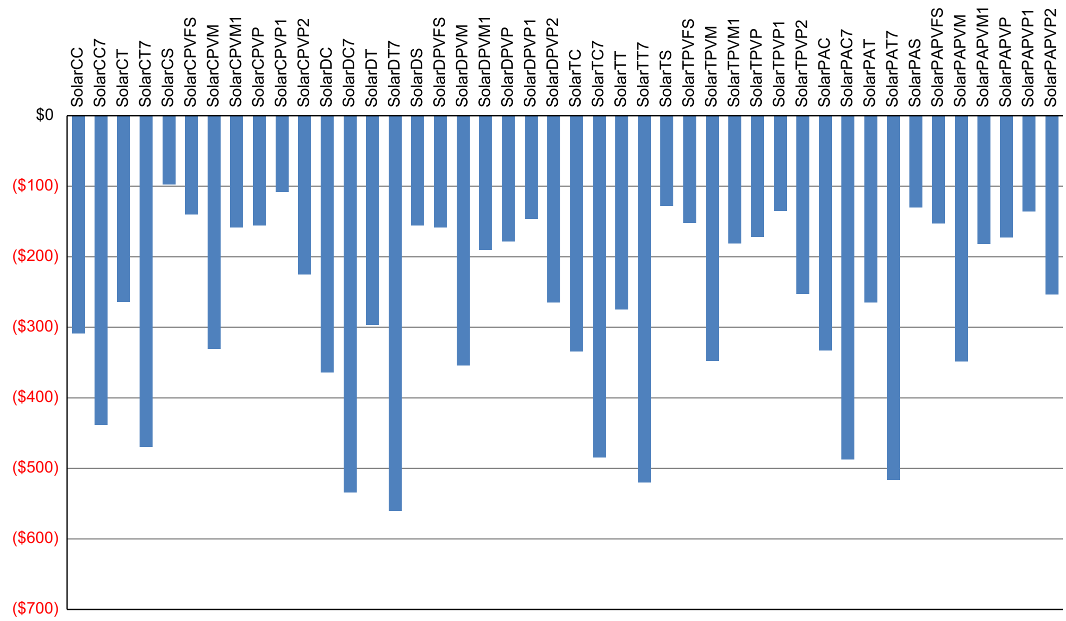

Fig. 9. Private NPV of the different solar power plants.

plant in the north of Chile is not economically beneficial for all solar technologies and localities studied.

Nonetheless, we must remark that the social economic evaluation performed does not include any benefit associated to either the improvements in the power-system reliability or the increment in labor rate due to the new solar power plant. Moreover, if we considered other positive externalities of installing solar power in the north of Chile or different economic conditions, the installation of a solar power plant in the north of Chile may be economically beneficial.

The private evaluation, considering an interest rate of 8% to compute the NPV, for the cases of thermal and PV technologies are shown in Tables 6 and 7, respectively. We found that the best location (from a private point of view) for installing solar power plants in northern Chile is Calama, result that is consistent with [13]. This is because a solar power plant installed in this location gives more electrical generation and more monetary income than in the other locations studied.

With respect to the technology, it was found that Stirling dish is the technology that gives the highest private NPV. Recall that cost data from this technology was taken from US Department of Energy Solar Energy Technologies Multi-year Program Plan [38].

With respect to the storage, it was found that is not economically beneficial to include it with parabolic trough or solar tower. For the case of a parabolic trough plant located in Calama, to add 7 h of thermal storage it represents a decrement of 129 millions of dollars to the private NPV and 145 millions of dollars to the social NPV (using an interest rate of 6%).

The results of the private economic evaluations of every solar power plant analyzed are shown in Fig. 9. This figure shows that, under the current market conditions, installing a solar power plant in the north of Chile is not economically beneficial for all solar technologies and localities studied. However, if we considered different economic conditions, the private NPV may be positive. For instance, if the price of carbon bonds change to 51.53 USD/TonCO_2, the Stirling-dish solar power plant in Calama is economically beneficial for the private evaluation at an interest rate of 8%. This would also happen if the government would give an economic incentive of 97.68 millions of USD for the construction of a 200 MW Stirling-dish solar power plant in Calama. In this scenario (a Stirling Dish solar plant in Calama), the break even capital cost is 2.33 million of USD/MW and the break even energy cost is 9.3 cents/kWh.

5. Conclusions

We have shown that it is possible to identify a limited number of variables that explain the variations on the investment cost of solar power plants. The investment cost of solar thermal power plants is mainly explained by their technology, capacity, area, storage capacity, and installed country. The results of the multivariable linear regressions performed show that the capacity is the most significant variable in explaining the investment cost, Chile is the less expensive country for the installation of a solar thermal power plant, and Stirling dish is the technology with the lowest investment cost. On the other hand, the investment cost of solar photovoltaic power plants is mainly explained by their technology, capacity, installation year, and installation country. The results of the multivariable linear regressions performed show that the capacity is the most significant variable in explaining the investment cost, Chile is the less expensive country for the installation of a solar photovoltaic plant, and that First Solar CdTe Thin Film is the technology with the lowest investment cost.

We simulated the long-term operation of the Chilean Northern Interconnected Power System (SING) to assess the economic impact of installing a solar power plant in the SING. The power plant with the highest reduction in the system marginal cost is a parabolic trough with 7 h of storage located in Calama. This is explained because this is the technology and location that generates the highest level of energy with the lowest marginal cost. It was found an average decrease of 26 millions of USD on the total system cost by introducing this solar power plant.

We also quantify the social (power-sector) and private net benefits of the installation of a solar power plant in the north of Chile and determine some conditions under which they are positive. The net present values of 11 different technologies were calculated for four different localities in the north of Chile. The results show that the best place for installing solar power plants (from a private viewpoint) is Calama, where more electrical generation and more monetary income are obtained than in the other locations studied. Considering the cost data from Stirling-dish project included in the

regression, this technology has the lowest NPV. Thermal energy storage is not economically beneficial for parabolic trough or solar tower power plants.

Since the results show that the NPV associated to some solar power plant projects are close to zero, higher carbon bonds prices or a small decrease in the cost of fuel prices could make positive some private NPV. For instance, if the price of carbon bonds change to 51.53 USD/TonCO_2, the Stirling-dish solar power plant in Calama is economically beneficial for the private evaluation at an interest rate of 8%. This may also happen if the government would give an economic incentive of 97.68 millions of USD for the construction of a 200 MW Stirling-dish solar power plant in Calama.

The break even capital cost and energy cost for a Stirling Dish solar plant in Calama are 2.33 millions of USD/MW and 9.3 cents/kWh, respectively. Moreover, considering all the positive externalities for consumers that this type of projects brings (which are not fully quantified in this research work), the social NPV can increase. This may eventually make the social NPV positive.

Finally, it is worth to mention that there are several international experiences about cost estimations of solar power plants. They vary in the methodology used and the trends of the results. However, one important lesson that one can take from the existing literature is that the cost estimation depend (in some way) on the local context of the power market. Accordingly, one might expect that policy makers (especially from developing countries like Chile) will pay more attention in the future to the local environment of power markets when planning power system expansions.

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